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THE MINERALOGY OF GLOBAL MAGNETIC ANOMALIES

PROGRESS REPORT

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INTRODUCTION

Our research participation in the MAGSAT mission has as the primary objective the acquisition of experimental and analytical data on the magnetic mineralogy of igneous and metamorphic rocks of crustal and upper mantle origin. These data are fundamental to the interpretation of magnetic models for the Earth's crust.

Our approach to this problem focuses on the determination of the Curie temperatures, magnetic susceptibilities and magnetic mineral chemistries of rock suites characteristic of the lower crust and upper mantle. Particular attention is concentrated on metamorphic rocks of predetermined grade, ultramafic suites which exhibit varying intensities of serpentinization, and xenoliths from alkali basalts and kimberlites. Complementary phase equilibria studies on the stability fields of oxides, sulfides and metal alloys aid in providing a comprehensive magnetic mineral data base for the interpretation of rock magnetization.

During the report period the Curie balance, which is central to our research, experienced several problems, which has severely hindered the acquisition of data; these have now been rectified and it is anticipated that the instrument will begin to function as intended. This hiatus has not affected our chemical analytical activities, which are proceeding satisfactorily. We have completed a survey of the magnetization characteristics of metamorphic suites and have compiled susceptibility data for a wide range of metamorphic and igneous rocks. These results form the basis of this report along with relationships between geology, gravity and MAGSAT anomalies of West Africa which have been extended from those previously presented.

Considerable data have been obtained on the magnetic mineralogy of the Koidu kimberlite in Sierra Leone and magnetic intensity data have been obtained through the cooperation of Professor R. Hargraves of Princeton University. In addition, approximately 500 new electron microbeam analyses on metals and oxides from the Josephine peridotite body in Oregon have been acquired. These data are presently not in a format suitable for presentation in this report. The kimberlite data from West Africa and the peridotite data from Oregon will be discussed in the next quarterly report.

PROGRESS REPORT

Data aquired by MAGSAT are at an unprecedented level of sensitivity and represent a substantial refinement of our understanding of the Earth's magnetic field, as exemplified by the remarkable resolution of global scale anomaly maps. However, interpretation of the anomaly data requires that our present state of knowledge be improved on the nature of the source rocks responsible for these anomalies, and in particular their magnetic mineralogy. Because large regions of the earth are characterized by igneous rocks, because substantial proportions of the continents are characterized by metamorphic suites, and because of the controversy surrounding the origin of deep seated magnetization and geomagnetic anomalies that are most commonly interpreted solely on the basis of induced magnetization, it is towards an evaluation of these observations, problems and assumptions that our efforts have been directed.

Because of the imposed constraints and our mineralogical orientation, our study has focused on an assessment of:

(a) trends in the magnetization of igneous rocks and the implications for oceanic magnetic anomalies;

(b) the relationship of rock magnetic susceptibility to magnetic mineral content;

(c) trends in the magnetization of metamorphic rocks, in particular the relation of metamorphic grade to magnetization; and

(d) potential magnetic sources in the lower crust and upper mantle.

The bulk of our samples are from West Africa and represent ground truth constraints. This, in association with a fragmented shield of the West African Craton, presents an opportunity for inter-continental correlation. The low magnetic latitude facilitates simple magnetic

modelling, and because of the striking correlation between geology, gravity, and MAGSAT anomalies described in the previous progress report, we have extended this work to include several different scales of gravity survey in an attempt to identify possible origins for satellite-observed magnetic anomalies.

The following section presents a synopsis of the five topics discussed above.

ROCK MAGNETIC SIGNATURES

(a) Magnetization of igneous rocks.

The common magnetic minerals are iron-titanium oxides, which are in general more highly oxidized and less abundant in acidic igneous rocks than they are in basic rocks. In addition to the oxides, pyrrhotite and some metal alloys are strongly magnetic and can contribute to rock magnetization. Because these minerals are essentially non-magnetic above their respective Curie temperatures, the geothermal gradient is critical in evaluating the depth of Curie isotherms. Figure 1a shows the oceanic and shield geotherms of Clark and Ringwood (1964), the common magnetic minerals and their Curie temperatures, the eclogite-basalt transition (Green and Ringwood, 1967) and the oxide minerals broadly typical of igneous rocks. It is clear from this diagram that, in theory, magnetization may be resident in igneous rocks far below the Moho discontinuity in direct contradiction to recent proposals.

(b) Magnetic susceptibility relationships.

Geomagnetic anomalies are frequently interpreted simply on the basis of magnetization induced in pure magnetite. A useful guide to interpretation is a plot of rock magnetic susceptibility versus volume percent magnetite and Figure 2 shows several such plots.

The data are compiled in the form of volume susceptibility in the cgs system; the equivalence in S.I. is shown on the far left ordinate of the figure. For rocks from the Adirondack Mountains the empirical relation is:

$$k = 2.6 \times 10^{-3} \text{ (vol \% magnetite)}^{1.11}$$

and for a Precambrain suite of rocks from Minnesota:

$$k = 2.89 \times 10^{-3} \text{ (vol \% magnetite)}^{1.01}.$$

Suceptibility and volume percent magnetite data assembled for a range of rocks types from diverse locations (Dunlop, 1974) plot close to the Adirondack and Minnesotan curves. Using these and other compilations of susceptibility data (Dobrin, 1976; Nagata, 1961) the relationship can be approximately calibrated for rock type as shown in Figure 2.

For pure magnetite as the sole magnetic mineral in a rock, the apparent rock magnetic susceptibility depends on the size, shape, and abundance of magnetite (Stacey and Bannerjee, 1974). Their theoretical relationship resolves to

$$k = 2.14 \times 10^{-3} \text{ (vol \% magnetite)}$$

also shown in Figure 2.

Magnetic susceptibility is thermally enhanced within 100°C or so of the Curie temperature of ferromagnetics; for magnetite the enhancement is by a factor of about two (Dunlop, 1974) and this is also shown in Figure 2.

In detail, the empirical curves show considerable scatter, but correspond closely to theory and to each other which is encouraging, notwithstanding that the relation is plotted in log-log space, since it appears to reflect the greater abundance of Fe-oxides in mafic igneous rocks.

(c) Magnetization of metamorphic rocks.

In igneous and metamorphic rocks from the South Indian Shield

susceptibility-density relationships appear to be weakly correlated to the metamorphic grade, which clearly increases rock density (Subrahmanyam and Verma, 1981), Figure 2. In the Ukraine Shield there is a marked increase of susceptibility with metamorphic grade (Krutikhovskaya and Pashkevich, 1979). Data from the Baltic Shield (see Figure 2), which represent about thirty thousand measurements, suggest that for general dioritic, mafic and ultramafic metamorphosed rocks the susceptibility is proportional to density (Henkel, 1976).

The susceptibility range 10^{-4} to 10^{-3} cgs is most typical of shield areas (e.g. Dunlop, 1974), so it is of note that the Indian rocks, collected for a density study, have rather high susceptibilities whereas the samples from Sweden, collected for general purposes, have susceptibilities less than 10^{-4} cgs; serpentinites are the exception. Whether there is a sampling bias involved, or whether this apparent disparity is a geologic reality is not clear.

The behavior of iron-titanium oxides in metamorphic rocks is not as well documented as it is for igneous rocks. A theoretical approach to this problem is presented in Figure 1b, which relates the metamorphic facies of regional metamorphism in temperature, depth and dry total pressure (Dobretsov et al., 1975; Ernst, 1975) to the shield geotherm and the Curie points of major magnetic minerals. The diagram represents the "best case" for continental magnetization in that the parameters are designed to allow a maximum of magnetization.

Oxide minerals can to some degree be correlated with metamorphic zones. In general, the chlorite zone is characterized by rutile and magnetite, the biotite zone has only rutile and ilmenite, and the garnet, staurolite and sillimanite zones have hematite, ilmenite and magnetite; on

prograde metamorphism from the chlorite zone a common reaction is:

rutile + magnetite → hematite + ilmenite

and titanium may be partitioned into silicate phases (Lidiak, 1974; Rumble, 1976). The long range result of these features will be high magnetic intensities in lower greenschist facies, low intensities in mid to high greenschist facies, and high intensities in high greenschist to upper amphibolite facies. Magnetic susceptibilities and magnetic anomalies should show a sinusoidal waveform over prograde metamorphic terrains.

(d) Magnetization of the lower crust and upper mantle.

High grade metamorphic rocks and mafic igneous rocks are typical of the lower crust and upper mantle of the earth, and long wavelength magnetic anomalies frequently require for their mathematical modelling, susceptibilities which are an order of magnitude higher than that usually measured for rocks at the surface. This susceptibility range is illustrated in Figure 2, where it is notably of the same magnitude as that for the Baltic Shield serpentinites. Serpentinite susceptibility is inversely related to density (Blakely and Page, 1980; Lienert and Wasilewski, 1977) and may in part be due to metal alloys (Haggerty, 1979).

Specific susceptibility measurements of lower crust-upper mantle xenoliths (Wasilewski et al., 1979) have been converted to volume susceptibilities (Table 1) in the data shown on Figure 2; these are lower than the commonly reported crustal rock range and are equivalent to the majority of the Baltic Shield measurements. Again, the problem is which rocks and which measurements are representative; serpentinized peridotites from the Deep Sea Drilling Project usually have low susceptibilities but remanent magnetizations in anomalously high susceptibility fields (Prevot and Dunlop, 1980; Irving et al., 1970) so that the source of deep seated

magnetic anomalies remains enigmatic.

MAGSAT, GEOLOGICAL, AND GRAVITY CORRELATIONS IN WEST AFRICA

(a) Local Bouguer gravity anomalies and geology of the Leo Uplift.

Positive Bouguer gravity anomalies over the Leo Uplift (Figure 2b) are coincident with the exposed Liberain Age shield rocks (migmatites, granites and magnetite quartzites metamorphosed at 2700 my) but the anomalies are probably due to higher density material beneath a locally thinned crust; negative anomalies are associated with sedimentarily thickened crust (Bronner et al., 1980).

Basaltic dike swarms associated with continental rifting strike parallel to the coast and kimberlite dikes and pipes pervade the area. On aeromagnetic maps of the region (e.g. Behrendt and Wotorson, 1974) the most conspicous anomalies are the basaltic dikes and iron formations such as those of Mount Nimba in Liberia.

(b) Regional Bouguer gravity anomalies.

A regional Bouguer map for Africa clearly shows that the East African Rift System ($\leq$ 1500 gu; 1 gravity unit = 0.1 milligal) and the Hoggar-Tibesti-Jebel Marra volcanic chain ($\leq$ 800 gu) are major features distinct from the rest of the continent. A model of thinned lithosphere, with a slightly lower density zone below, generates anomalies very similar to those observed, and lithospheric thinning of only 15 km (to 85 km) is sufficient to model the -800 gu Hoggar Uplift anomaly (Brown and Girdler, 1980).

In West Africa the exposed shield areas are less than -400 gu, the Taoudeni Basin is between zero and -400 gu and the craton is bounded in the east by the -400 gu contour.

(c) Free air gravity anomalies.

In the Atlantic Ocean, ground based long wavelength positive free air gravity values are coincident with a positive residual depth anomaly over the volcanic Azores Islands; these anomalies cannot be lithosphere supported and probably are the signature of an upwelling mantle source (Sclater et al., 1975), see Figures 3a and 3d.

The spherical harmonic coefficients of satellite-derived free air gravity maps represent sources of about 500 to 100 km depth for degree and order 12 and sources between 50 and 300 km for degree and order 13-22 (e.g. Kahn, 1971; Marsh and Marsh, 1976; Tarakanov and Cherevko, 1979); the higher degree and order models closely correspond to the ground based data of Figure 3a in our study area (Marsh and Marsh, 1976).

Comparison of Goddard Earth Model (GEM) 8 in Figures 3i-j (Wagner et al., 1977) with Gem 10 in Figures 3g-h (Marsh, 1979) and the ground based geology and gravity data (Figures 3a, b, d) shows that the Azores is a prominent feature in all of the maps; it is a strong feature also of the low degree gravity field. The Hoggar Uplift has no clear expression in the low degree field but is very prominent in the higher harmonics; the Leo Uplift is central to a major positive feature of the low degree and order field, and is visible but less distinct in the higher harmonic coefficients.

(d) Gravimetric model.

A model of density contrasts derived from constraints imposed by the Bouguer and free air gravity anomalies requires a deep (asthenosphere) rising region of relatively low density, associated with regional uplift of southern West Africa; the positive satellite free air anomaly is due to the mass excess of the uplifted surface layer. The negative regional

Bouguer anomalies may be due to less dense material at the base of the lithosphere filling in for slightly uplifted or thinned lithosphere.

Extensive lithospheric thinning does not seem to apply to the region of the Fouta-Djallon and Leo Uplift, so that the local positive Bouguer anomalies probably have the lower crustal source postulated by Bronner et al. (1980), which is discrete from the satellite free air anomaly source.

(e) Magnetic-gravimetric correlations.

For West Africa and the adjacent Atlantic Ocean there is general correspondence of satellite gravity anomalies with the POGO and MAGSAT maps, compare Figures 3c, h, j. Where gravity is positive, the magnetic maps are negative or are of subdued intensity. Comparisons of satellite gravity and magnetic fields and other long wavelenth anomalies have shown diverse relations between the two potential fields, although continental rifts and oceanic trenches tend to have this inverse sign correspondence (e.g. Frey, 1979a; Ruder and Frey, 1981; von Frese et al., 1979; 1981). Neither errors in the gravity field models nor density contrasts in the outer earth are capable of generating the observed magnetic anomalies (Taylor et al., 1981).

On the West African Craton, the Reguibat Shield and the Leo Uplift are negative magnetic anomalies and positive free air gravity anomalies, whereas the Taoudeni Basin is a magnetic high and a gravity low. Local and regional Bouguer, satellite free air and satellite magnetic anomalies all show pronounced discontinuities coincident with the Proterozoic (Frey, 1979b) suture which bounds the craton in the east, see Figures 3a, d, g-j.

(f) Magnetic models.

It is unlikely that the negative magnetic anomaly over the Leo Uplift is a function of heat flow alone since shields are typically low heat flow

provinces and, at least for the United States (von Frese et al., 1979), heat flow seems to modulate rather than determine the satellite observed magnetic anomaly field.

The main geomagnetic field over the uplift is essentially horizontal (Figure 3b and 3f) so that if the negative anomaly is due to induced magnetization the susceptibility contrast must be positive; if it is due to remanence the magnetization must have been acquired during a normal field episode.

Viscous remanence generated in the present field is one possibility, and thermal remanence reset during Cretaceous rifting when the magnetic polarity was normal for an unusually long period is another possible origin for the magnetic signature.

In the case of induced magnetization there are a number of possible sources including:

(1) deep seated, mafic intrusives; (2) the granulite basement terrain; (3) basaltic dike swarms; and (4) exposed metamorphic iron formations.

The first possibility could be related to the negative regional Bouguer and free air anomalies if relatively low density material of high susceptibility, for example serpentinites, is emplaced within the lower lithosphere, or it may be related to the local Bouguer anomalies if the intrusives are emplaced at lower crustal levels or just below the Moho where the same rock might have a positive density contrast. The latter possibility is compatible with a model of a thin magnetic layer close to the Moho as developed by Hall (1974); in both models gravity and magnetic anomalies are due to the same source.

An alternate model by Hall (1974) might be compatible with the

basement terrain as the source, in which the entire lower crust is strongly magnetic. In this case, and in the two previous suggestions, thermally enhanced susceptibility could be operative.

The basalt dikes and iron formations are not responsible for gravity anomalies at the map scales we have examined, but they may be related to the magnetic anomaly field. Although short wavelength features such as dikes attenuate rapidly with height, basaltic rocks are generally highly magnetic (Figure 2) and it is conceivable that the integrated magnetization of a large dike swarm could form a broad, low amplitude anomaly at very high altitude.

One of the largest iron ore deposits in the world is a Kursk in the U.S.S.R. (at about 51°N 36°E), which is also the locus for one of the most intense positive anomalies on both POGO and MAGSAT total field maps; the difference in sign is expected because of the difference in geomagnetic latitude, about 70°N at Kursk. Similar deposits to those in the Leo Uplift occur at Fort-Gouraud, Mauritania, on the Reguibat Shield at 22°N 12°W. This model is, perhaps, rather prosaic compared to the previous suggestions, but is useful for global correlation and is clearly and immediately related to the exploration for natural resources.

SUMMARY

Considerable progress has been made during the report period in establishing long range trends in the magnetic signatures of abundant rock types typical of the crust and mantle of the Earth. These include:

(1) igneous rocks and their characteristic magnetic mineralogies (Figure 1a) and susceptibilities (Figure 2);

(2) metamorphic rocks and their characteristic magnetic mineralogies (Figure 1b), susceptibilities and densities (Figure 2); and

(3) lower crustal and upper mantle rocks (Figures 1 and 2).

In addition, we have established a correlation between the gravity signatures, geologic provinces and MAGSAT anomalies for West Africa (Figure 3), and have developed multiple working hypotheses for the source of MAGSAT anomalies in this region.

PROBLEMS

Severe problems have been encountered with the installation of the Curie balance due to manufacturer's oversight. These range in magnitude from faulty electrical connections within the amplifier to a total mismatch of components between the cryostat assembly and the balance vacuum chamber. Fundamentally, the problems arose due to a lack of quality control and testing before shipment. The vendor has replaced the faulty components gratis and their representatives have visited our laboratory to aid with the installation of the instrument. The final replacement parts arrived in December, 1981 and full operational status is now imminent.

Although this has prevented magnetic analysis concurrent with the geochemical program it has not been a great hindrance, except for the aggravation, and all effort has been directed toward the mineralogical and geochemical aspects. However, in the absence of magnetic analytical data no substantive conclusions can be made from these data alone.

PLANNED RESEARCH

The next and most urgent stage of our research program will be the determination of the magnetic properties of a large backlog of samples on which mineral and geochemical data have already been acquired.

Based on the encouraging results of visual comparisons between several geological and geophysical data sets for West Africa, the next logical step in this direction will be to undertake a similar analysis for South America. Also, the data so far assembled may be suitable for a more sophisticated, mathematically-based correspondence analysis and the feasability of this approach will be evaluated.

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FIGURE CAPTIONS

Figure 1a. Magnetic minerals and intrusive suites. This figure shows the dominant magnetic oxide phases of gabbroic and granitic suites and their inferred Curie temperature ranges, with the Curie points of major magnetic minerals (Haggerty, 1976a; 1976b; 1979), the shield and oceanic geotherms (Clark and Ringwood, 1964), and the basalt-eclogite transition (Green and Ringwood, 1967).

Figure 1b. Magnetic minerals and regional metamorphism, illustrating the facies of regional metamorphism in terms of dry total pressure, temperature (°c) (Dobretsov et al., 1975; Ernst, 1975), and the Curie points of major magnetic minerals.

Figure 2. Relationships of apparent magnetic susceptibility with volume percent magnetite and rock density. On the left is the empirical relationship of magnetic susceptibility and rock density for rocks from the Baltic Shield (outlined areas, Henkel, 1976) and the South Indian Shield (data points): charnockites and ▽ rocks are from high grade (granulite) terrain, △ rocks are from low grade (granulite-greenstone) terrain (Subrahmanyam and Verma, 1981). On the right, empirical relations of susceptibility with volume percent magnetite for rocks from the Adirondacks (Balsley and Buddington, 1958), Minnesota (Mooney and Bleifuss, 1953) and diverse locations (Dunlop, 1974), along with the theoretically predicted relationship (Stacey and Bannerjee, 1974), a 2 fold thermally enhanced susceptibility (Dunlop, 1974), and typical average susceptibility ranges (Dobrin, 1976; Nagata, 1961). Named rocks are from Minnesota (Mooney and Bleifuss, 1953). Xenolith susceptibilities (Wasilewski et al.,

1979; Table 1) are shown with horizontal bars and the anomalously high susceptibility range for deep magnetic sources is illustrated. Note that the left and right vertical scales are equivalent: k (S.I.) = 4 π k (cgs).

<u>Figure 3a-j</u>: Geology and geophysics of West Africa and the adjacent North Atlantic Ocean:

<u>Figure 3a</u>. Gravity and elevation anomalies. In the Atlantic: solid line shows smoothed Free Air gravity anomalies (in milligals) derived from ground-based data; dashed line shows smoothed residual depth anomalies in hundreds of meters (Sclater et al., 1975). Continental Bouguer gravity anomalies (Slettene et al., 1973) are contoured at 400 g.u. intervals (1 gravity unit = 0.1 milligal).

<u>Figure 3b</u>. Regional geology of West Africa.

Precambrian shield . . . .

Major sedimentary basins . . . .

Paleozoic and mesozoic fold belts . . . .

Fold/mobile belt . . . .

<u>Figure 3c</u>. MAGSAT total field anomaly map. Contour interval 2nT in oceans, 4nT in continents.

Negative . . . . Positive . . . .

<u>Figure 3d</u>. Tectonic elements.

Areas of regional uplift . . . .

Recent volcanism . . . .

Kimberlite localities . . . .

Continental rift region . . . .

Mid-Atlantic Ridge . . . .

Oceanic basin . . . .

Thrust fault . . . .

(Lowman and Frey, 1979; Dawson, 1980; Le Bas, 1971)

<u>Figure 3e</u>. Filtered POGO total field magnetic anomalies (Frey et al., 1979). POGO features which persist on MAGSAT are more reliable than new features.

. . . . -2nT. . . . . +2nT.

<u>Figure 3f</u>. Geomagnetic inclination (Wyllie, 1976). Magnetic anomaly signatures will vary with geomagnetic inclination, which changes within the area from roughly horizontal to greater than 60°N.

<u>Figure 3g</u>. GEM 10 Free-Air gravity anomalies for degree 22 (Marsh, 1979). Contours in milligals. There is a substantial high over the Azores and a negative over the West African craton.

<u>Figure 3h</u>. GEM 10 Free-Air gravity anomalies for degree 13-22 (Marsh, 1979). Most of the previous features persist, but a discrete positive anomaly close to Cape Verde has emerged.

<u>Figure 3i</u>. GEM 8 Free-Air gravity anomalies for degree 22 (Wagner et al., 1977). Essentially similar to Figure 3g.

<u>Figure 3j</u>. GEM 8 Free-Air gravity anomalies for degree 13-22 (Wagner et al., 1977). Note the correspondence between satellite gravity data (Figure 3j, Figure 3h) and ground based gravity data (Figure 3a), and the inverse relationship with POGO (Figure 3e) and MAGSAT (Figure 3c) magnetic anomalies.

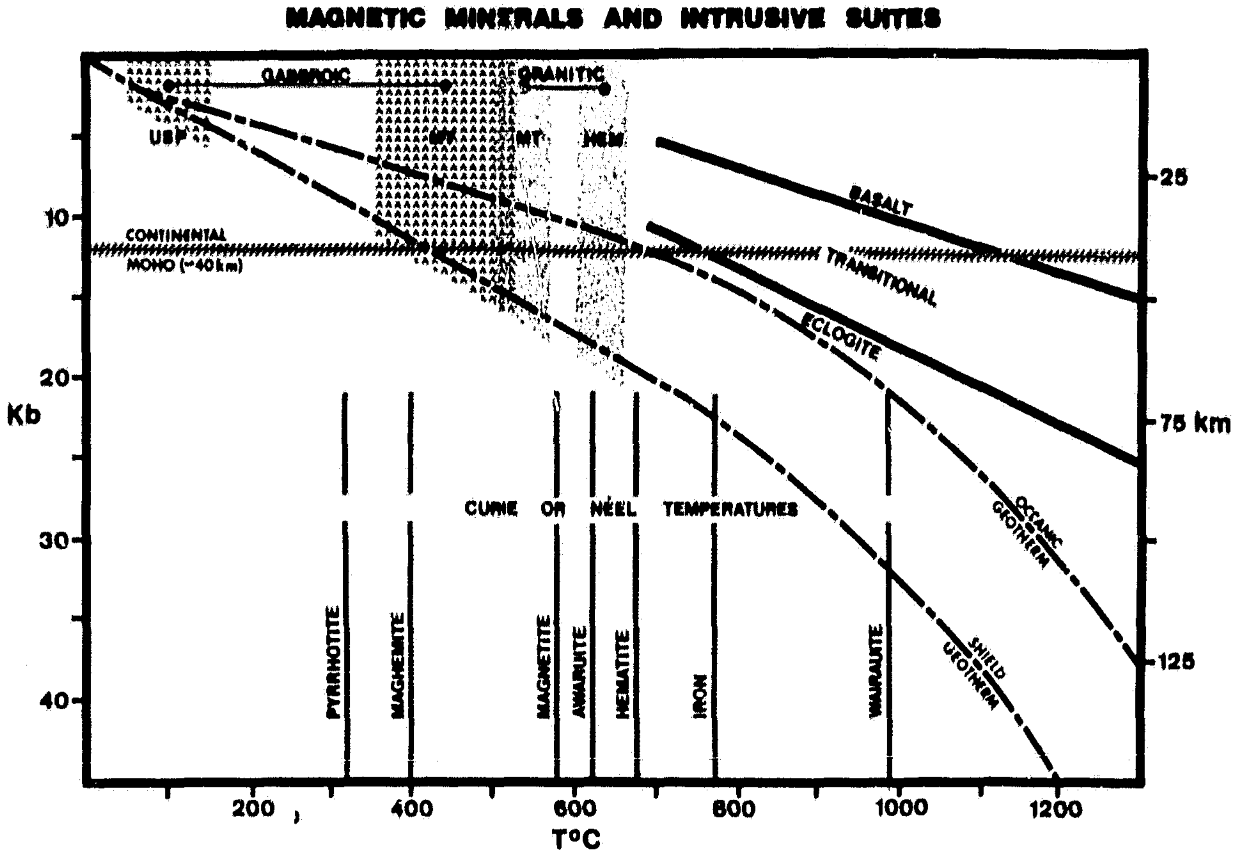
MAGNETIC MINERALS AND INTRUSIVE SUITES
GABBROIC
GRANITIC
USP
MT
MT
HEM
BASALT
TRANSITIONAL
ECLOGITE
CONTINENTAL
MOHO (~40km)
CURIE OR NÉEL TEMPERATURES
OCEANIC
GEOTHERM
SHIELD
GEOTHERM
PYRRHOTITE
MAGHEMITE
MAGNETITE
AWARUITE
HEMATITE
IRON
WAIRAUITE
Kb
10
20
30
40
25
75 km
125
200
400
600
800
1000
1200
T°C

Fig 1a

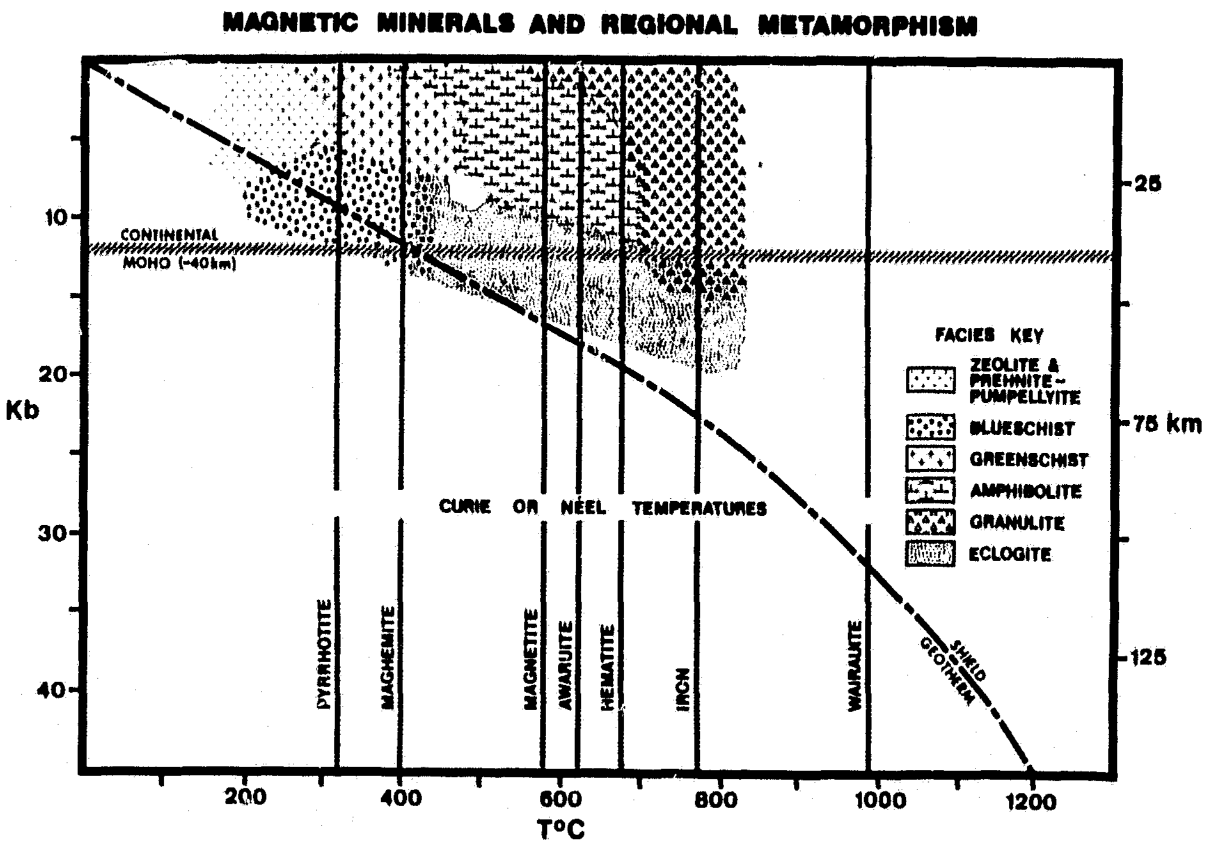
MAGNETIC MINERALS AND REGIONAL METAMORPHISM
CONTINENTAL
MOHO (~40km)
FACIES KEY
ZEOLITE &
PREHNITE -
PUMPELLYITE
BLUESCHIST
GREENSCHIST
AMPHIBOLITE
GRANULITE
ECLOGITE
CURIE OR NÉEL TEMPERATURES
SHIELD
GEOTHERM
PYRRHOTITE
MAGHEMITE
MAGNETITE
AWARUITE
HEMATITE
IRON
WAIRAUITE
Kb
10
20
30
40
25
75 km
125
200
400
600
800
1000
1200
T°C

Fig 1b

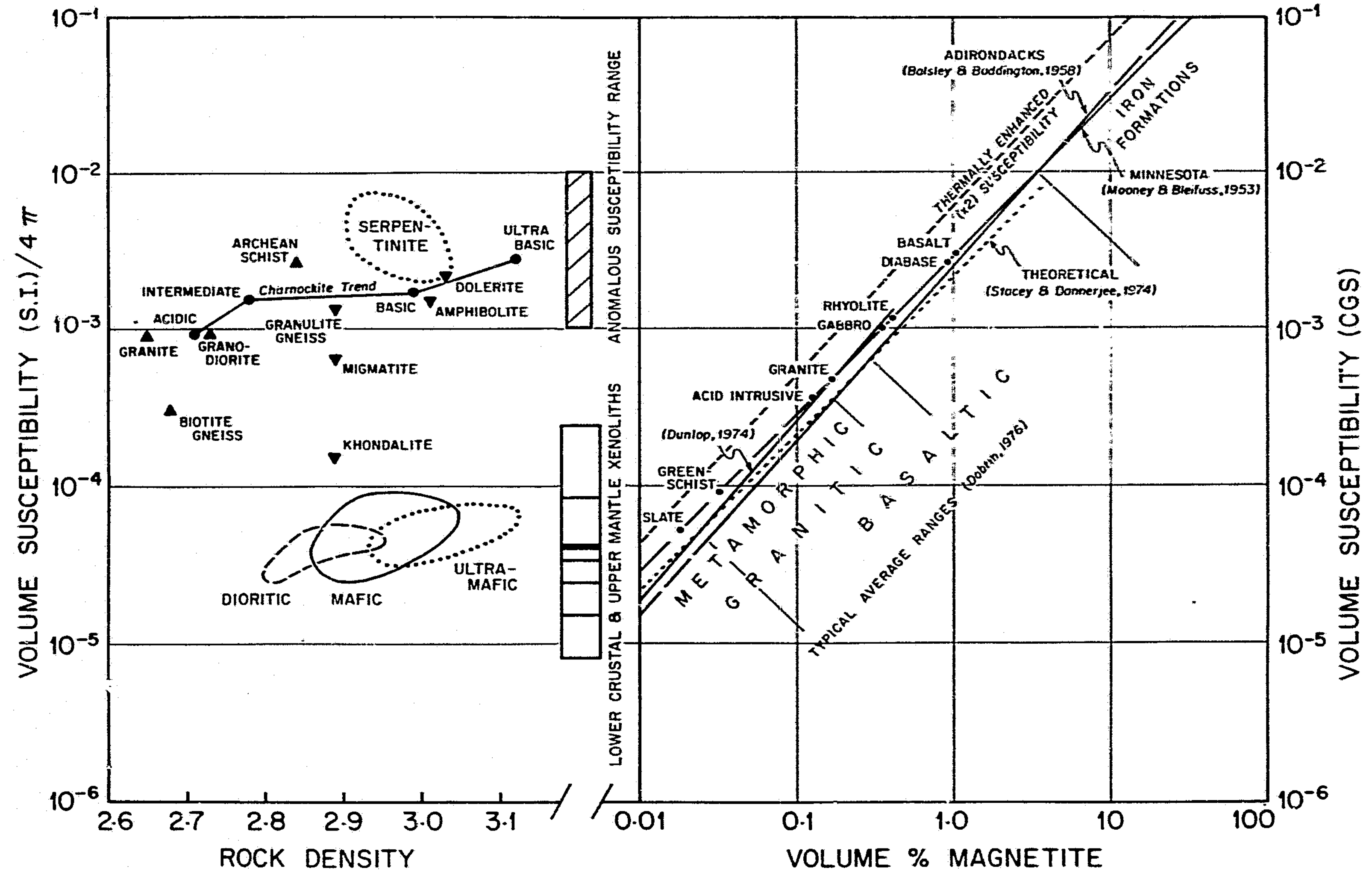
VOLUME SUSCEPTIBILITY (S.I.)/4 π
VOLUME SUSCEPTIBILITY (CGS)
ROCK DENSITY
VOLUME % MAGNETITE
ANOMALOUS SUSCEPTIBILITY RANGE
LOWER CRUSTAL & UPPER MANTLE XENOLITHS
SERPEN-TINITE
ARCHEAN SCHIST
ULTRA BASIC
INTERMEDIATE
Charnockite Trend
DOLERITE
BASIC
AMPHIBOLITE
ACIDIC
GRANULITE GNEISS
GRANITE
GRANO-DIORITE
MIGMATITE
BIOTITE GNEISS
KHONDALITE
DIORITIC
MAFIC
ULTRA-MAFIC
ADIRONDACKS (Balsley & Buddington, 1958)
THERMALLY ENHANCED (x2) SUSCEPTIBILITY
IRON FORMATIONS
MINNESOTA (Mooney & Bleifuss, 1953)
BASALT
DIABASE
THEORETICAL (Stacey & Banerjee, 1974)
RHYOLITE
GABBRO
GRANITE
ACID INTRUSIVE
(Dunlop, 1974)
GREEN-SCHIST
SLATE
METAMORPHIC
GRANITIC
BASALTIC
TYPICAL AVERAGE RANGES (Dobrin, 1976)

Fig 2

ORIGINAL PAGE IS OF POOR QUALITY

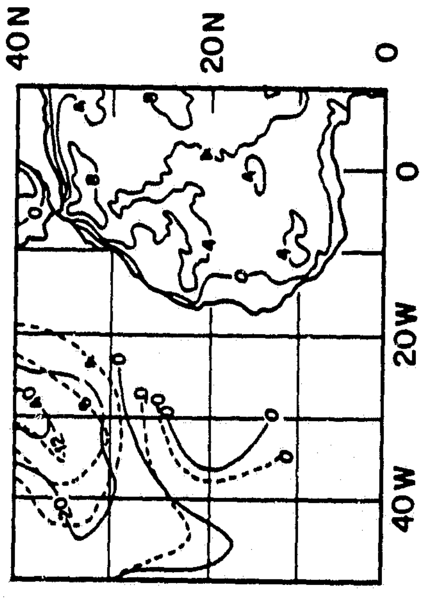

Fig. 3a

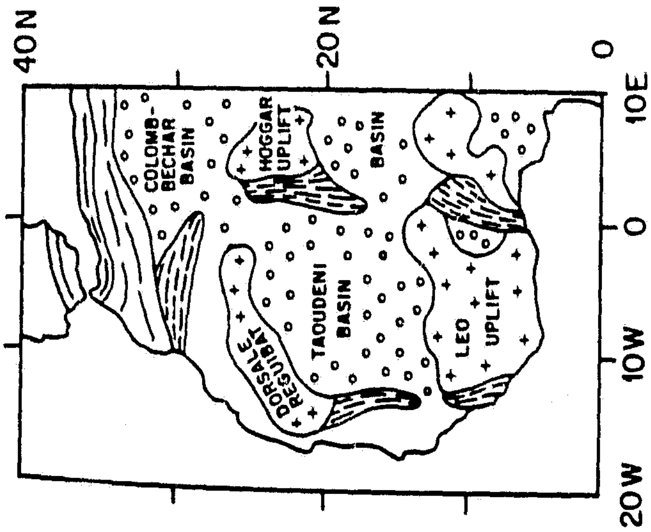

Fig. 3b

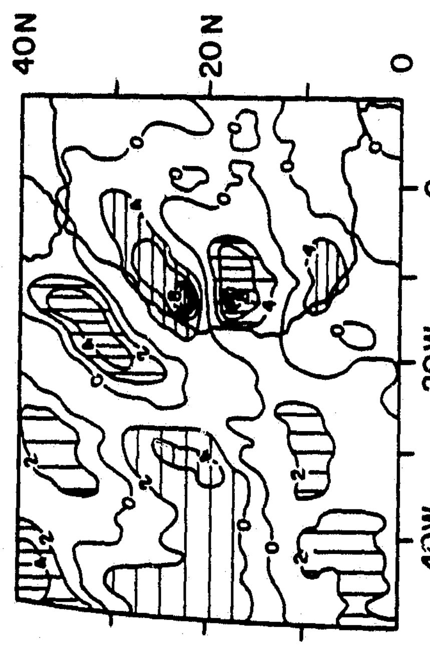

Fig. 3c

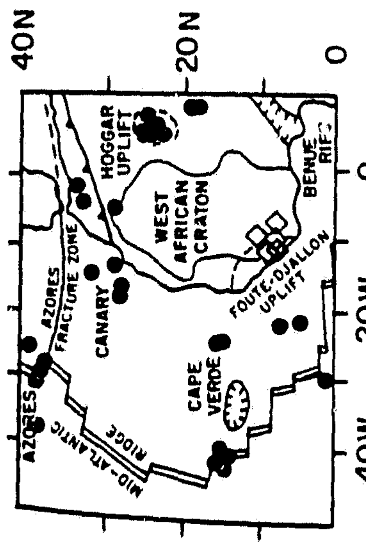

Fig. 3d

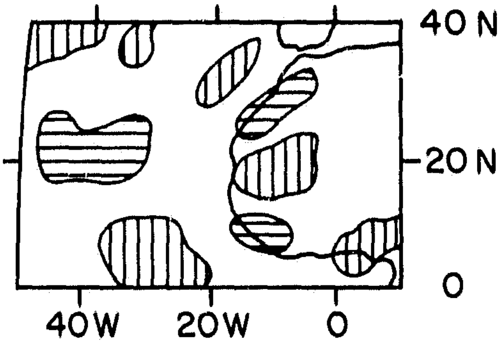

Fig. 3e

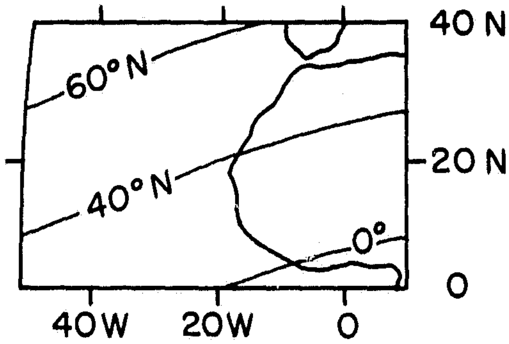

Fig. 3f

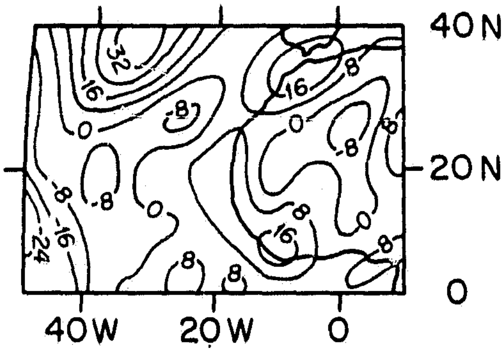

Fig. 3g

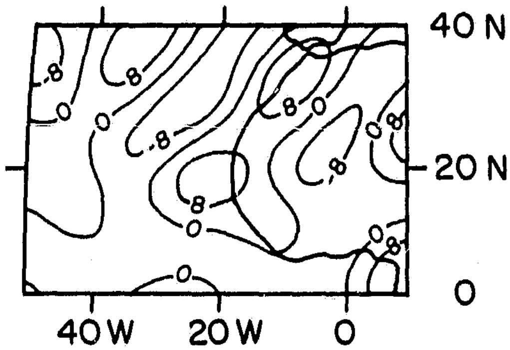

Fig. 3h

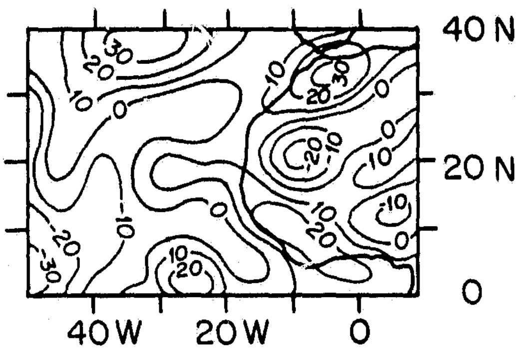

Fig. 3i

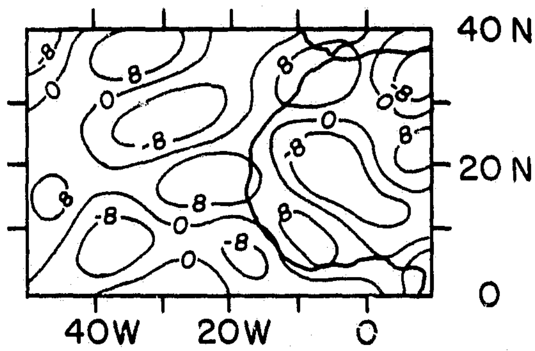

Fig. 3j

TABLE 1 Susceptibilities and Densities of Lower Crust-Upper Mantle Xenoliths

Xenolith type	Specific Susceptibility cgs x 10^{-6}	Density gm/cm^3	Volume Susceptibility cgs x 10^{-5}
Eclogite	9.7	3.39	3.3
Eclogite	9.6	3.39	3.3
Peridotite	7.5	3.23	2.4
Garnet Peridotite	73.6	3.23	23.8
Pyroxenite Nodule	12.5	3.2	4.0
Brown Peridotite	25.7	3.23	8.3
Peridotite	12.7	3.23	4.1
Olivine Nodule	3.52	4.39	1.5
Olivine Nodule	1.76	4.39	0.8

(Wasilewski et al., 1979)

(Daly et al., 1966; Robie et al., 1966)